

Potential for Areawide Integrated Management of Mediterranean Fruit Fly (Diptera: Tephritidae) with a Braconid Parasitoid and a Novel Bait Spray

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ABSTRACT The braconid wasp, *Fopius arisanus* (Sonan), a biological control agent for Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), was studied in coffee, *Coffea arabica* L. *Fopius arisanus*, comprised 79.3% of the total parasitoids (7,014) recovered from fruits collected at three small coffee farms. Data from seasonal host/parasitoid studies at a large coffee plantation also suggested that the most effective natural enemy of *C. capitata* in coffee may now reside in Hawaii. The original parasitoids introduced into Hawaii for *C. capitata* control (*Diachasmimorpha tryoni* (Cameron), *Tetrastichus giffardianus* Silvestri, and *Dirhinus giffardii* Silvestri) are now rare. Abundance of *F. arisanus* with respect to other parasitoids collected was influenced by elevation (274, 457, 610 m). *Fopius arisanus* was the dominant parasitoid at all three elevations, *Diachasmimorpha longicaudata* (Ashmead) occurred consistently, and *T. giffardianus* was abundant only at low elevation. The impacts on *C. capitata* and *F. arisanus* populations of bait sprays containing malathion, spinosad, or phloxine B applied to coffee were also evaluated. All three bait sprays suppressed *C. capitata* populations. Spinosad and phloxine B bait sprays appeared less harmful to the wasp than malathion. *Fopius arisanus* offers the potential for areawide management of *C. capitata* that includes biological control and integration with more environmentally safe chemical controls such as spinosad and phloxine B bait sprays.

KEY WORDS *Ceratitis capitata*, *Fopius arisanus*, biological control, bait sprays, areawide control

FRUIT FLIES (DIPTERA: Tephritidae) are among the most economically important pests attacking soft fruits worldwide (White and Elson-Harris 1992). One of the most costly species is the Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann). Its host range includes >350 species of fruits and vegetables (Liquido et al. 1991) and costs to exclude it from areas such as California have totaled almost \$500 million during the past 25 yr (Carey 1991, 1999). Classical biological control of insects results from the introduction and establishment in new localities of exotic natural enemies (i.e., predators, parasitoids, and pathogens) for control of either introduced or native pests (Van Driesche and Bellows 1993). Tropical fruit flies generally have not proved to be good candidates for classical biological control with the exception of two major successes achieved in Hawaii (Waterhouse 1993).

Ceratitis capitata was accidentally introduced into the Hawaiian Islands from Australia ≈1907 and it became a serious pest of tree fruits including guava (*Psidium guajava* L.), citrus (*Citrus* spp.), mango (*Mangifera indica* L.), loquat [*Eriobotrya japonica* (Thunb.) Lindl.], and peach [*Prunus persica* (L.) Batsch] (Back and Pemberton 1918). Natural enemies [*Diachasmimorpha tryoni* (Cameron), *Opius humilis* Silvestri, *Tetrastichus giffardianus* Silvestri, and *Dirhinus giffardii* Silvestri] were first introduced in 1913 and 1914, primarily as a result of an expedition to Africa by Silvestri (1914). Although many natural enemies were established in Hawaii, the only crop where conspicuous biological control of *C. capitata* occurred was coffee (*Coffea arabica* L.), where *D. tryoni* from Australia outcompeted two other braconid parasitoid wasps and became the dominant species (Doutt and DeBach 1964).

When oriental fruit fly, *Bactrocera dorsalis* (Hendel), was introduced into Hawaii in 1945, it displaced *C. capitata* throughout most of its range, except in areas growing coffee and upper elevation localities with preferred *C. capitata* hosts (Vargas et al. 1983, Nishida et al. 1985). With the introduction of *B. dorsalis*, the largest program in classical biological control against fruit flies was undertaken to reduce the serious damage occurring in fruits. A total of 32 natural ene-

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mies was released between 1947 and 1952 (Bess et al. 1961). *Diachasmimorpha longicaudata* (Ashmead) increased rapidly following its release in 1948, but suddenly lost its dominant position during the later half of 1949 to *Fopius vandenboschi* (Fullaway), which was later superseded by *Fopius arisanus* (Sonan), a braconid wasp introduced in 1950 from the Malay peninsula with other opiine parasitoids, but misidentified initially as *Opius persulcatus* Silvestri (van den Bosch and Haramoto 1953, Ramadan et al. 1992). *Fopius arisanus* oviposits in eggs, *F. vandenboschi* in first-instar larvae, and *D. longicaudata* in second and third instars of tephritid hosts (van den Bosch and Haramoto 1953). All three species emerge as adults from the tephritid-pupal stage. Although *B. dorsalis* occurs throughout the orient, *C. capitata* does not. Since its establishment, *F. arisanus* has resulted in a dramatic reduction in infestation of fruit in Hawaii through a high level of *B. dorsalis* parasitization (65–70%), and has remained the dominant parasitoid species (Haramoto and Bess 1970). Although many studies have evaluated biological control of *B. dorsalis* in Hawaii, only a few have examined the nontarget beneficial impact of parasitoids released against *B. dorsalis* on *C. capitata*. Clausen et al. (1965) suggested that *F. arisanus* not only had displaced other *C. capitata* parasitoids but also had greatly reduced the abundance of *C. capitata* throughout Hawaii, but they provided only circumstantial data. Limited data collected in 1967–1968 at Kona, HI, suggested that *F. arisanus* had also become the dominant parasite attacking *C. capitata* in coffee (Haramoto and Bess 1970). No studies to clarify the situation were undertaken until the 1990s.

During the last decade, Hawaiian agriculture has been in transition with major declines in both sugarcane (*Saccharum officinarum* L.) and pineapple [*Ananas comosus* (L.) Merr.] cultivation and an increase of alternative crops. One new development has been the planting of large areas of former sugarcane land with coffee. Although *B. dorsalis* displaced *C. capitata* throughout most lowland habitats during the late 1940s, *C. capitata* is now recolonizing these lowland coffee areas. This is not surprising because *C. capitata* and coffee evolved together in east Africa (Vargas et al. 1995). Nonetheless, *C. capitata* is more common now in Hawaii than anytime since the introduction of *B. dorsalis* (Vargas et al. 1995).

Recolonization by large *C. capitata* populations in lowland coffee growing areas has presented rare opportunities to investigate different biological control strategies for *C. capitata* that include classical biological control, augmentative parasitoid releases, conservation of natural enemies, and integration of natural enemies with selective and environmentally safe chemical controls (Knipling 1992, Stark and Vargas 1992, Purcell 1998, Peck and McQuate 2000). Reported here are the results of recent research in commercial coffee-growing areas on Hawaii and Kauai Islands that document the effects of the following: (1) elevation on *F. arisanus* abundance, (2) *F. arisanus* on *C. capitata* in an agro-ecosystem throughout a coffee season, and (3) protein bait sprays with the novel

insecticides spinosad and phloxine B on *C. capitata* and *F. arisanus* abundance.

Materials and Methods

Three ecological studies were conducted: (1) Parasitoid surveys at three elevations on small coffee farms at Kahaluu, Kealahakua, and Captain Cook, Hawaii Island, HI, from day of year (DOY) 280, 1994 until DOY 75, 1995; (2) *B. arisanus* host and seasonal parasitization studies at Kona Mountain Coffee Farm, Kainiliu, Hawaii Island, HI, from DOY 213, 1997 to DOY 78, 1998; and (3) impacts of bait sprays on *C. capitata* and *F. arisanus* populations at Kauai Coffee Plantation, Kalaheo, Kauai Island, HI, from DOY 266, 1998 to DOY 19, 1999. In this study the term "DOY" is used to numerically designate days between 1 January and 31 December. It is employed in place of the terms Julian Date, Julian Day, or JD, which are often misused for this purpose (Wilimovsky 1990). All samples of coffee fruits were processed at the USDA-ARS-Pacific Agricultural Research Center, Hilo, HI.

Parasitoid Surveys at Three Elevations. The Kona area on Hawaii Island has consistently supported a large *C. capitata* population caused by widespread commercial coffee production. Elevation is a major factor determining fruit fly abundance in various habitats of Hawaii, with larger populations of *C. capitata* found infesting host fruits at upper elevations (Nishida et al. 1985). To obtain current information (since 1968) on the status of *C. capitata* parasitoids in coffee, a survey of natural enemies was conducted on coffee farms at three elevations. Three commercial coffee farms located at 274 (Kahaluu), 457 (Kealahakua), and 610 m (Captain Cook) were selected. This survey differed from previous studies in that both tree and ground fruit were examined to ensure that late larval and pupal parasitoids attacking ground fruits would be represented. One hundred ripe coffee fruits were placed in a screened capture box (30.5 by 30.5 by 10.2 cm) for 1 wk. Underneath each box a tray containing 1 kg of moist sand was secured. The tray contained 12 drainage holes screened with nylon tent screening (Lumite, Gainesville, GA) to prevent pooling of rainwater. The top of the capture box was also screened with 1 by 1-cm hardware cloth. Larvae fell through the screen on the bottom into the sand where they were still subject to parasitoid attack, but protected from predators such as birds and rodents. To prevent ant predation the box was elevated above the ground by four 12.7-cm lengths of 2.5-cm-diameter PVC pipe. Tanglefoot (Tanglefoot Company, Grand Rapids, MI) was placed around the legs.

In each orchard a grid of 15 equal quadrants was flagged. At the center of each quadrant a capture box was placed at the base of a coffee plant. Shade from coffee plants prevented lethal temperatures from occurring inside the capture box. Each week beginning in early October 1994, 100 ripe fruits were collected from trees found within a 5-m radius of each box. The amount of fruit collected for each sample was dependent upon the amount of fruit available within the 5-m

radius of the collection boxes. Another 100 fruits were placed inside recovery boxes along with fresh sand. After 1 wk the sand and fruit were removed and replaced with new coffee fruits.

Immediately after collection from the recovery box the sand used in the tray was sifted using a circular sieve (USA Standard Sieve, no. 18, 1-mm mesh; Newark Wire Cloth, Newark, NJ). Paired samples of tree and ground fruits were weighed in the laboratory and placed on a metal screen inside 5.2-liter plastic containers (Highland Plastics, Pasadena, CA, no. 49, 9.2 cm diameter by 4.7 cm high) with screened lids containing slightly moistened sand. The holding room was maintained at $22 \pm 5^\circ\text{C}$, ambient relative humidity 40–90%, and a photoperiod of 12:12 (L:D) h. Sand from the buckets was sifted weekly. Both tree and ground fruits were held for at least 3 wk. Larvae and pupae sieved from samples were transferred to small plastic cups (Highland Plastics, no. 74, 9.2 cm diameter by 4.7 cm high) with screened lids containing slightly moistened sand. These cups were held in a room maintained at $21 \pm 5^\circ\text{C}$, ambient relative humidity (45–80%), and a photoperiod of 12:12 (L:D) h. Emerged fruit flies and parasitoids inside cups were counted and sexed. Parasitoids were identified to species with the taxonomic keys of Beardsley (1961) and Wharton and Gilstrap (1983). Unknown specimens were sent to the USDA-ARS, Systematic Entomology Laboratory, Beltsville, MD, for conclusive identification.

***P. arisanus* Host and Seasonal Parasitization.** Because both *C. capitata* and *B. dorsalis* attack coffee in the Kona area, collections of infested fruits yield mixed populations of fruit flies. To identify which host *F. arisanus* was attacking, parasitization rates for *C. capitata* and *B. dorsalis* pupae were determined separately as described by Vargas et al. (1995). Fifteen samples of 100 fruits were collected approximately each week for 30 wk from a 2-ha field at Kona Mountain Farm (elevation 600 m) near Kainiliu. Samples were collected from five coffee plants in 15 separate rows. Rows were selected using a random numbers table. Fruits were held inside plastic containers (Highland Plastic no. 36, 14.5 cm diameter by 15.5 cm high) that contained 1.5 cm of sand in an environmental cabinet (Convion, Asheville, NC) maintained at $25 \pm 2^\circ\text{C}$, $60 \pm 10\%$ RH, and a photoperiod of 12:12 (L:D) h and pupae recovered. Pupae were identified as either *C. capitata* or *B. dorsalis* (Yamada et al. 1962) and transferred to small plastic containers (Highland Plastics no. 74, 9.2 cm in diameter by 4.7 cm high) with 0.5 cm of sand until emergence of flies or parasites. Numbers of *C. capitata* or *B. dorsalis* and the parasitoid, *F. arisanus*, were recorded. Dead pupae were dissected to determine if parasitism had occurred. Percentage parasitism was calculated on the basis of live and dead *F. arisanus* recovered from total pupae.

Effects of Bait Spray on *C. capitata* and *F. arisanus*. The 1,375-ha planting of coffee (elevation 122 m) at the Kauai Coffee Plantation on Kauai Island is currently the greatest single source of natural *C. capitata* production in Hawaii (Vargas et al. 1995). Hundreds

of plants are grown per hectare in open sunlight and a single plant produces thousands of fruits. Coffee fields are heavily infested with *C. capitata* and provide an ideal location for development of control strategies. Recently, the effects of bait sprays containing malathion, and two novel insecticides, spinosad and phloxine B, were compared for reduction of *C. capitata* in coffee fields (Peck and McQuate 2000). As a concurrent nontarget study, we examined the effects of bait sprays on *F. arisanus* populations. The bait solution contained 70% (vol:vol) Mazoferm E802 (Corn Products, Argo, IL), 20% (vol:vol) invertose (Liquid Sugar, Inc., Emeryville, CA), 6.0% (vol:vol) water, 2.0% (vol:vol) polyethylene glycol 200 (ICN Biomedicals, Aurora, OH), 1.0% (vol:vol) polysorbate 60 (Soco-Lynch, Los Angeles, CA), 1.0% soybean oil (Hunt-Wesson, Fullerton, CA), and 0.6% (wt:vol) ammonium acetate (Sigma, St. Louis, MO). The spinosad bait solution consisted of 0.01% (AI) (wt:wt) spinosad active ingredient (a mixture of Spinosyn A and Spinosyn D) mixed into the protein bait just described. The spinosad (NAF-315; lot # MB11160P21) was provided by Dow AgroSciences (Indianapolis, IN). This sample consisted of 22.8% (AI). The phloxine B bait solution included 0.5% (wt:wt) phloxine B (89.0% purity; Hilton-Davis, Cincinnati, OH) and the protein bait just described. The malathion bait solution consisted of 20% technical malathion (Fyfanon ULV, Cheminova, Wayne, NJ) and 80% NuLure (Miller Chemical and Fertilizer, Hanover, PA). Weekly spraying began on DOY 308 and ended on DOY 355, for a total of eight sprays. Rate of application of bait sprays averaged 15 liters/ha (malathion bait spray) and 22 liters/ha (spinosad and phloxine B). The spray was applied through two Tee jet 5500-X2 (for malathion bait) or two Tee Jet 5500-X3 (for spinosad and phloxine B) cone jet spray nozzles, one on each side, set to deliver splotches to coffee plants, attached to a boom at the back of an all terrain vehicle. Details of the experimental layout are given in Peck and McQuate (2000).

Random samples of 1,000 fruits (three-fourths to fully ripe) were collected weekly from treatment plots (two plots each for spinosad, malathion, and phloxine B) and untreated controls (two plots). In each plot 25 fruits were collected from each of 10 points, determined by a randomly selected interval of one to five plants, in four randomly selected rows. Numbers of *C. capitata* and *B. arisanus* to emerge were compared from DOY 213, 1998 until DOY 64, 1999. Fruits were weighed and placed in batches of 1,000 on a wood-framed metal screen (43 by 28 by 6 cm) inside fiberglass holding boxes (50 by 32 by 15 cm) that contained 1.5 cm of sand and were held for 3 wk. Sand from large fruit holding boxes was sifted weekly. Pupae were transferred to smaller plastic containers until emergence of flies or parasitoids. Fruits were held in a room maintained at $22 \pm 5^\circ\text{C}$, ambient relative humidity (40–90%), and a photoperiod of 12:12 (L:D) h and recovered pupae in an environmental cabinet maintained at $25 \pm 2^\circ\text{C}$, $60 \pm 10\%$ RH, and a photoperiod of 12:12 (L:D) h. Numbers of *C. capitata* and *B. arisanus*

that emerged were recorded. We dissected dead pupae to determine if parasitism had occurred.

Statistical Methods. For survey data, parasites recovered from fruits for each elevation were totaled and the proportion by species transformed to percentages. Counts by elevation of the egg parasitoid and non-egg parasitoids were compared using a G-test for independence (Sokal and Rohlf 1969). Numbers of *C. capitata* and *F. arisanus* recovered from coffee fruits in the bait spray test were transformed to $\ln(x + 1)$ to stabilize variances. *C. capitata* and *F. arisanus* data were analyzed with repeated-measures analysis of variance (ANOVA). We analyzed four dates each for the pretreatment, treatment, and posttreatment phases. A probability level of 0.05 was used as the significance criterion for all statistical tests (SAS Institute 1987).

Results

Parasitoid Surveys at Three Elevations. Six species of parasitoids were recovered from coffee fruits collected at three farms: four braconids (*F. arisanus*, *D. longicaudata*, *Psytalia incisi* (Silvestri), and *D. tryoni*), a eulophid (*T. giffardianus*), and a chalcid (*D. giffardii*). Percentages of the total number (7,014) were as follows: *F. arisanus* (79.3%), *D. longicaudata* (13.4%), *T. giffardianus* (5.7%), *D. tryoni* (1.5%), and *P. incisi* (0.1%), and *D. giffardii* (0.1%). Total numbers collected at 274, 457, and 610 m elevation were 1,322, 2,863, and 2,829, respectively (Fig. 1). *Fopius arisanus* was the dominant (53.6–88.4% range) parasitoid at all three elevations, *D. longicaudata* occurred consistently (10.0–16.8% range), and *T. giffardianus* was abundant (0.7–27.4% range) only at low elevation. All other parasitoid species were rarely encountered. The frequency of the egg parasitoid (with respect to non-egg parasitoids) was dependent on elevation ($P < 0.001$, $df = 2$, $\chi^2 = 616.4$). Only six specimens of the pupal parasitoid *Dirhinus giffardii* Silvestri were collected during the survey. Parasitoid abundance, in terms of stage attacked, were the egg-larval parasitoid (*F. arisanus*) > larval parasitoids (*D. longicaudata*, *T. giffardianus*, *D. tryoni*, and *P. incisi*) > the pupal parasitoid (*D. giffardii*). *Tetrastichus giffardianus* and *P. incisi* were absent from tree-collected fruits, suggesting that they primarily forage for hosts within ground fruit. *Dirhinus giffardii* was recovered only from pupae held in boxes on the ground. This is the first time this species has been sampled during recent field surveys in Hawaii. *Diachasmimorpha longicaudata* and *D. tryoni* were recovered from both tree and ground fruit, suggesting that foraging occurs both in the tree and on the ground. However, ground fruits sampled may have harbored parasites already inside tree fruits that had recently fallen on the ground.

***Fopius arisanus* Host and Seasonal Parasitization.** Relative abundance of *C. capitata* and *B. dorsalis* throughout the 1997–1998 coffee season at Kona Mountain Farm is illustrated in Fig. 2 (lower portion). During the early season (DOY 213–240) abundance of *C. capitata* was higher than *B. dorsalis*. Thereafter

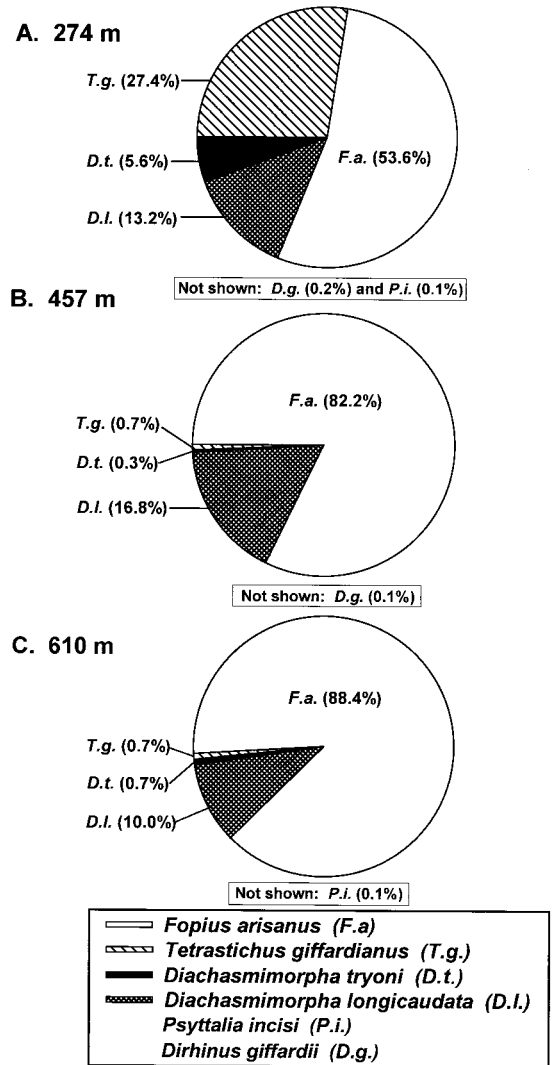


Fig. 1. Percentage of parasitoids from ≈ 15 samples of 100 fruits collected at three Kona (Hawaii Island, HI) commercial coffee farms located at (A) 274 m (Kahaluu, $N = 19$ dates), (B) 457 m (Kealahakua, $N = 21$ dates) and (C) 610 m (Captain Cook, $N = 23$ dates) elevation.

(DOY 247 until DOY 50), numbers of *C. capitata* and *B. dorsalis* were similar with the exception of higher *B. dorsalis* abundance from DOY 324 to 338. After DOY 50, *C. capitata* became the most abundant species. *Fopius arisanus* was an important mortality factor throughout the coffee season attacking both species of fruit flies. Mean percentage (\pm SEM) of *F. arisanus* to emerge from both *C. capitata* or *B. dorsalis* increased throughout the early season, remained high throughout midseason, and decreased throughout the late coffee season. A grand total of 5,096 pupae was recovered from coffee fruits of which 3,269 were *C. capitata* and 1,827 were *B. dorsalis*. Rates of parasitization (number of *F. arisanus*/number of *C. capitata* or

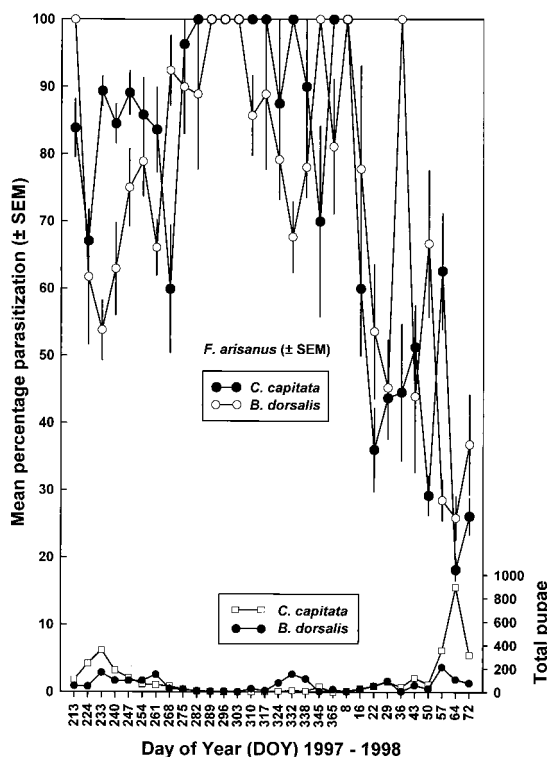


Fig. 2. Percentage (mean \pm SEM) of *F. arisanus* to emerge from 15 samples of 100 fruits collected weekly at Kona Mountain Coffee Farm (elevation 600 m) near Kailua, Hawaii Island, HI. Numbers of *C. capitata* and *B. dorsalis* pupae recovered weekly are illustrated on the lower portion of the graph.

B. dorsalis pupae) were 42.9% for *C. capitata* and 53.5% for *B. dorsalis*.

Effects of Bait Spray on *C. capitata* and *F. arisanus*. Numbers of *C. capitata* and *F. arisanus* to emerge from samples of 1,000 fruits collected during the 1998–1999 coffee season from the control plots at Kauai Coffee Plantation are illustrated in Fig. 3. With ripening of coffee fruits (DOY 266–294), a rapid increase in *C. capitata* numbers occurred between DOY 294 and 315, and the major buildup of *F. arisanus* occurred between DOY 294 and 334. After DOY 355, *F. arisanus* was the most abundant insect recovered from coffee fruits.

During the pretreatment phase, numbers of *C. capitata* in the treatment plots were not significantly different from the control ($F = 1.35$; $df = 3, 4$; $P = 0.3778$) (Fig. 4). With eight weekly applications of bait sprays (DOY 308–355), there was a rapid decline in *C. capitata* reared from fruits. Throughout the bait spray treatment period, all treatment plots differed significantly from the control plots ($F = 28.37$; $df = 3, 4$; $P = 0.0037$), although *C. capitata* was reared periodically from coffee fruits sampled from all treatment. With the cessation of bait sprays, there began an increase in fruit infestation in all treatment plots from DOY 362 (1998) to 19 (1999). However, numbers of *C. capitata* recovered from fruits collected in treatment plots

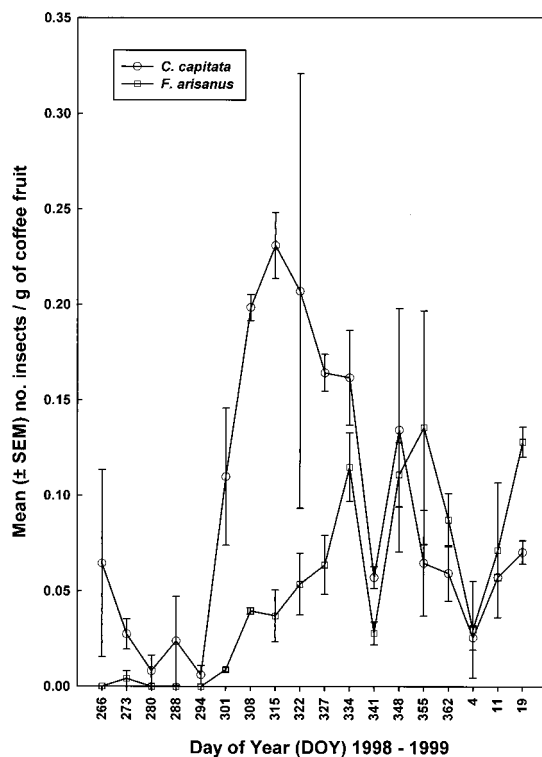


Fig. 3. Numbers (mean \pm SEM) of *C. capitata* and *F. arisanus* to emerge from samples of 1,000 fruits collected during the 1998–1999 coffee season at Kauai Coffee Plantation in coffee fields near Kalaheo, Kauai Island, HI.

were still significantly lower than those from the control plot ($F = 65.01$; $df = 3, 4$; $P = 0.0008$).

During the pretreatment phase numbers of *F. arisanus* in treatment plots were not significantly different from the control ($F = 1.00$; $df = 3, 4$; $P = 0.4800$) (Fig. 5). *Fopius arisanus* declined rapidly (DOY 308–322) with the suppression of *C. capitata*, but rebounded with the cessation of treatments (DOY 362–19). During the treatment phase numbers of *F. arisanus* in treatment plots were significantly different from control plots ($F = 1724.25$; $df = 3, 4$; $P = 0.0001$). During the posttreatment phase numbers of *F. arisanus* in treatment plots were still significantly different from the control ($F = 7.60$; $df = 3, 4$; $P = 0.0396$). However, mean (\pm SD) cumulative numbers of parasitoids recovered from malathion, phloxine B, and spinosad plots were 2.6 ± 1.06 , 21.0 ± 12.39 , and 60.2 ± 20.19 wasps per 1,000 fruits, respectively. Recolonization was slower in malathion treated fields than in the spinosad and phloxine B treated fields. Furthermore, within 2 wk of the last bait spray, the wasp became the most abundant insect emerging from coffee fruits collected from spinosad plots.

Discussion

During the 20th century *C. capitata* has been the target of numerous expeditions to collect natural en-

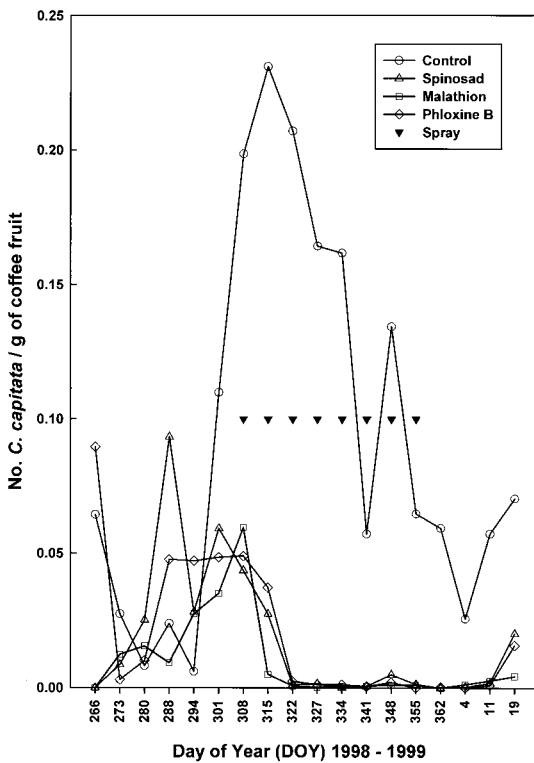


Fig. 4. Numbers of *C. capitata* to emerge from coffee samples of 1,000 fruits collected weekly from treatment and control plots at Kauai Coffee Plantation near Kalaheo, Kauai Island, HI.

emies. Africa, the original home of the *C. capitata*, has been the area explored most often (Silvestri 1914, Steck et al. 1986). Interestingly *C. capitata* has origins in Africa, while *F. arisanus* has origins in Southeast Asia. It was through a beneficial nontarget effect of classical biological control of *B. dorsalis* that these two insects met in Hawaii. The results document an effective biological control system for *C. capitata* in coffee that has developed over the past 50 yr. The data and a literature review suggest that the most effective natural enemy of *C. capitata* in coffee may now reside in Hawaii. Our field results suggest that although three different types of parasitoids (egg-pupal, larval-pupal, and pupal) are active against *C. capitata* and *B. dorsalis*, the egg-pupal parasitoid, *B. arisanus*, appears to have an insurmountable advantage in the parasitoid guild because it attacks host eggs close to the surface of fruits and apparently inhibits development of competing larval-pupal parasitoids that attack a later host stage often dispersed throughout the fruit (van den Bosch and Haramoto 1953). Furthermore, the original parasitoids (*D. tryoni*, *T. giffardianus*, and *D. giffardii*) brought to Hawaii for *C. capitata* control by Silvestri are now rare. Parasitoids introduced for *B. dorsalis* control during the late 1940s and early 1950s (i.e., *F. arisanus* and *D. longicaudata*) are now the major natural enemies of fruit flies in coffee. Finally, there

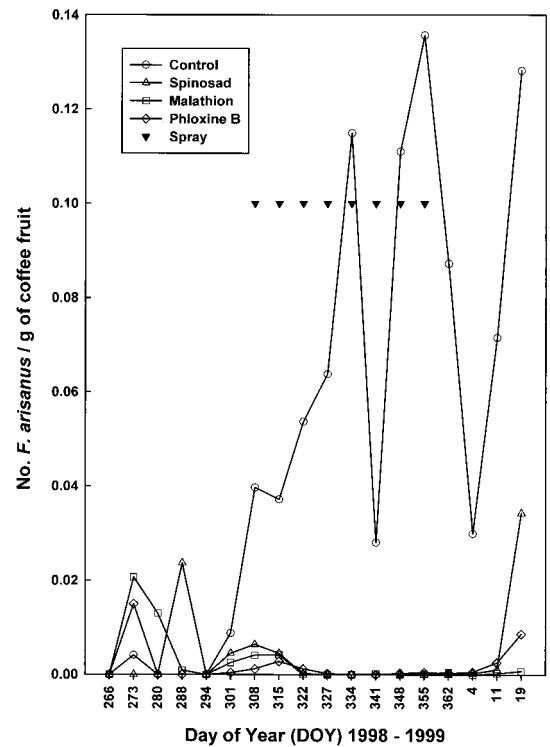


Fig. 5. Numbers of *F. arisanus* to emerge from coffee samples of 1,000 fruits collected at Kauai Coffee Plantation near Kalaheo, Kauai Island, HI.

appears to be little elevational effect (274–610 m) on the ecological range of *F. arisanus*. However, elevation did significantly affect the abundance of *F. arisanus* with respect to other parasitoids, most notably at low elevation.

Because mixed populations of *C. capitata* and *B. dorsalis* infest coffee, there has always been the possibility that *F. arisanus* was emerging only from *B. dorsalis* pupae. However, this is not the case. Studies at the Kona Mountain Farm near Kainiliu are the second time individual parasitization rates have been obtained and confirm earlier findings on Kauai Island, where *C. capitata* was heavily attacked by *F. arisanus* (Vargas et al. 1995). However, unlike the Kauai Island study where, except at the beginning of the season, *B. dorsalis* rarely infested the coffee, during the Hawaii Island study *B. dorsalis* persisted throughout the coffee season. Nonetheless, by the end of the coffee season *C. capitata* was the dominant species.

The large population of *C. capitata* at the Kauai Coffee Plantation has been the target of areawide suppression programs during the last 10 yr. Previously, our laboratory attempted to control the large *C. capitata* population using the sterile insect technique. With the release of almost 1 billion sterile flies during 1991, the wild population was suppressed by 56% compared with a control (Vargas et al. 1994). In the current study we examined the seasonal effect of *F. arisa-*

mus on *C. capitata* with and without bait sprays. The population dynamics observed suggests a typical parasite/host relationship (Doutt and DeBach 1964). With an increase in the host, *F. arisanus* begins attacking *C. capitata* and increases in numbers. Eventually by the end of the coffee season the wasp becomes the dominant insect reared from coffee fruits. Previous experience at the Kauai Coffee Plantation suggests that this relationship between *C. capitata* and the wasp occurs on a yearly basis and is representative of not only our study plots, but also the entire plantation (Vargas et al. 1995). Recently, Peck and McQuate (2000) reported on field tests of two environmentally friendly malathion replacements, spinosad and phloxine B. Although malathion was found to be the most effective treatment, spinosad and phloxine B gave significant levels of control. Our results also suggest that all bait spray treatments significantly reduced numbers of *C. capitata* and *F. arisanus* in treatment plots, compared with those in control plots. However, we do not know whether reductions of *F. arisanus* were due to decreases in its host or decreases in numbers of adult parasitoids in treated fields. Nonetheless, *C. capitata* was still active in treatment fields throughout the season, albeit at low numbers, and with the cessation of bait sprays recolonized test plots (spinosad > phloxine B > malathion). It is recognized that *C. capitata* is not an economic pest of coffee in Hawaii, and with the extensive biological control occurring, there would be little need to treat this crop except to decrease *C. capitata* movement to other crops. However, these small-scale tests against large *C. capitata* populations present a worst-case scenario for suppression attempts. For immediate *C. capitata* suppression with bait sprays, large areas would have to be treated repeatedly with insecticides, eventually leading to environmental consequences. Nonetheless, the rapid recolonization of treatment areas by *F. arisanus* and the higher abundance of the parasitoid compared with its host in spinosad and phloxine B test plots suggest that this wasp might be integrated with these materials for areawide *C. capitata* control. Field cage tests indicated that leaves picked 2 wk after plants were sprayed with malathion, spinosad, or phloxine B baits caused ~95, 25, and 25% mortality, respectively, when exposed to flies for 6 h (Peck and McQuate 2000). These results would support our data showing a lack of buildup of flies and parasites in malathion plots and a more rapid buildup in spinosad and phloxine B plots. Laboratory tests showing high susceptibility of parasitoids to malathion bait sprays (Hoy and Dahlsten 1984) and low susceptibility of parasitoids to phloxine B bait sprays (Dowell 1997) would support this approach. Because crops in the present test had to be destroyed 4 wk after cessation of spraying, a longer posttreatment period was not possible and more tests on the susceptibility of parasitoids to phloxine B and spinosad bait sprays are necessary. Laboratory and field cage studies are presently being conducted.

Use of bait sprays for suppression of fruit flies and the mode of kill for the three compounds tested (malathion, spinosad, and phloxine B) merit comment.

Malathion kills insects by contact or vapor action and is also a stomach poison (Matsumura 1975). Bait droplets applied to a single leaf may saturate nearby leaves. Thus, any insect landing on a contaminated leaf may die. However, spinosad kills primarily by ingestion with only limited contact kill (DowElanco 1994). Phloxine B kills entirely by ingestion (Heitz 1995). Although the protein added to the poison in bait sprays is not as attractive to flies as natural sources of food, the protein is consumed by many hungry flies (Prokopy et al. 1992). *Fopius arisanus* does not feed on the bait (R.I.V., unpublished data). Therefore, it would appear that spinosad or phloxine B would be better choices than malathion from an environmental standpoint for control of *C. capitata* and conservation of *F. arisanus*. Presumably, with spinosad and phloxine B bait treatments, the host would be killed, but not the natural enemy. Future integrated pest management (IPM) research for fruit flies should emphasize optimization of the protein included in bait sprays for attraction, so that the nontarget effects of broad spectrum contact poisons such as malathion can be avoided.

Present research in Hawaii is focusing on mass production and augmentative releases of *F. arisanus* into areas where parasite numbers may be low (Bautista et al. 1999). Furthermore, the integration of techniques such as environmentally acceptable bait sprays with conservation of natural enemies for area-wide IPM of fruit flies (i.e., Mediterranean fruit fly, oriental fruit fly, melon fly, and Malaysian fruit fly) is being examined. These approaches may also have broader applications. The most recent source of *C. capitata* invading the continental United States has been identified as Central America (Haymer et al. 1997). One of the major breeding sources of *C. capitata* in Central America is coffee. It is estimated that the total area of coffee cultivation in southern Mexico and Central America in 1998 was 1.5 million hectares (FAO 1998). Control options in this area have recently been restricted by a ban on aerial applications of bait sprays containing malathion for fruit fly suppression in Guatemala. Consequently, this area should be given consideration as a future site for *F. arisanus* releases, which may provide area-wide reduction in *C. capitata* populations. Technology currently being developed in Hawaii could be easily transformed into a classical biological control program in Central America. Furthermore, this regional suppression approach may be supplemented in areas where bait sprays are required to prevent the northward migration of *C. capitata* (viz., southern Mexico and Guatemala) with spinosad and phloxine B bait sprays. Previously, *F. arisanus* was released and recovered in Costa Rica; however, little information is available on its present status or distribution in coffee (Wharton et al. 1981).

Enthusiasm for the potential of *C. capitata* control in Central America should be tempered with a critical analysis of the possible negative nontarget effects of biological control (Ehler 2000). Since *F. arisanus* was introduced into Hawaii over 50 yr ago, no significant impacts to native insects have been shown (Duan and

Messing 2000). However, we have presented ample evidence that this insect has expanded its host range to include *C. capitata* from its previously recorded host, *B. dorsalis*. For this reason we recommend that host specificity testing take place before this species is released into additional areas.

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